Global water retention in forest canopy, litter, and soil layers and its controlling factors

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Abstract: Forest ecosystems play a vital role in the earth's hydrological process, and precipitation intercepted by forests accounts for more than a quarter of the water in the terrestrial hydrologic cycle. However, water retention in the three layers (canopy, litter, and soil) of forest ecosystems has not yet been thoroughly investigated on a global scale. Here, we investigate the global pattern of forest water retention capacity (WRC) and its controlling environmental factors based on 982 observations of 21 controlling factors in the three forest layers, mainly from 1990 to 2018. The results show that global WRC varies among the different forest types and climatic zones with a mean of 456.71 mm, while the average total water storage is 22,662.47 km^3 in forest ecosystems. Climatic variables are the leading factors contributing to the variations in forest WRC, followed by forest structure factors, soil properties, terrain factors, and litter factors. This study advances our understanding of the mechanisms underlying large-scale variations in forest WRC in different climate zones and forest types. The findings demonstrate that controlling factors should be considered when developing policy for regions with important ecological functions. They also provide a benchmark to improve ecohydrological models for simulating global WRC.

Forest water retention refers to the interception, buffering, and storage of precipitation in forest ecosystems through three vertical layers: canopy[1], litter[2], and soil[3]. Forest water retention is important for the supply of freshwater, water quality, hydrology and climate regulation, and soil and water protection[4, 5]. Vegetation is widely recognized as an important consideration in assessments of water resources[4]. For example, forest ecosystems designated for soil and water protection cover an area of 1015×10^4 km^2 according to FAO's Global Forest Resources Assessment[6]. The American forest-covered regions[7, 8] and South American rainforests[9] recycle over 50% of precipitation to maintain ecosystem function and integrity. However, the global pattern of forest water retention capacity (WRC) and the factors controlling WRC in forest ecosystems have not yet been investigated.

Due to the high monetary and labor costs required for long-term observations as well as the absence of open digital data[10], WRC has been difficult to assess on a global scale using only field measurements. Some ecosystem service models such as the Integrated Valuation of Ecosystem Services and Trade-offs model (InVEST) and Artificial Intelligence for Ecosystem Services (ARIES) can be used to simulate WRC globally; however, the simulation results typically lack large-scale validation with observed data. The Gravity Recovery and Climate Experiment mission (GRACE) tracked icesheet and glacier ablation, groundwater depletion, reservoir changes, surface water, and soil moisture[10, 11, 12, 13, 14]. However, like the above models, the GRACE satellites could not further divide the global WRC pattern into multiple forest layers (i.e., canopy, litter, and soil).

Although factors contributing to WRC have been individually evaluated, it is difficult to comprehensively understand forest WRC without clarifying the relative effects of location, terrain, climatic factors, forest structure, litter characteristics, and soil properties. Precipitation has been reported as a major determinant of water storage[15]. The effects of changes in forest cover on watersheds have been evaluated using paired experiments[16]. Vegetation cover and climate can have offsetting or additive effects on changes in water resources in forested regions[4]. However, the effects of various factors on water retention remain unclear because the individual effects are difficult to distinguish when multiple factors interact with each other. In this study, we employed structural equation modeling (SEM) to build a bridge between empirical and mechanical methods, quantify the effects of the factors influencing WRC, and better understand the water cycle of forest ecosystems.

We collected 982 observations in 43 countries and regions from 254 peer-reviewed articles to reveal the global pattern of WRC and its spatial variance in multiple forest layers (Fig. 1). This approach allowed us to extend small-scale studies to the global scale and overcome the infeasibility of large-scale WRC field measurements.

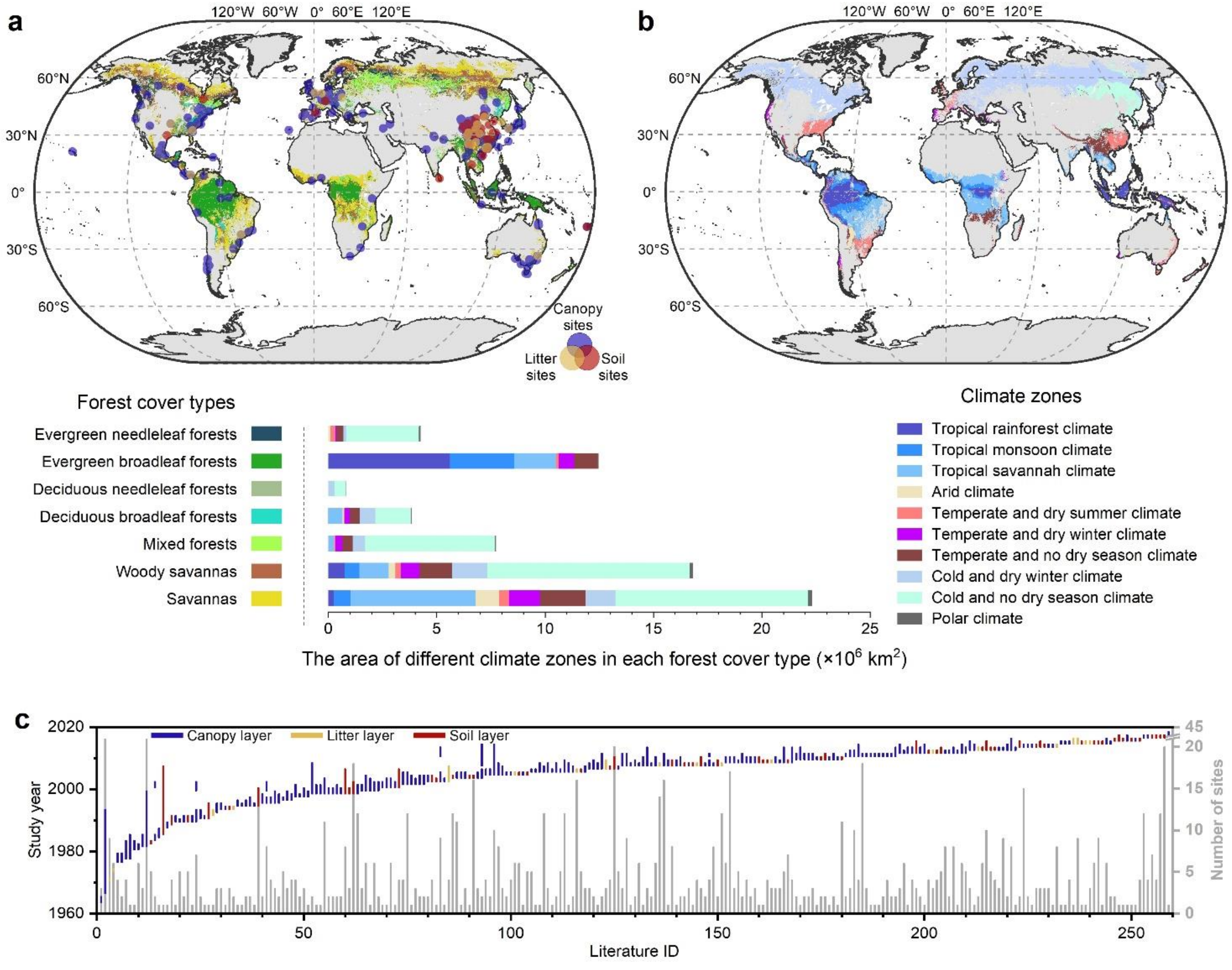

Fig. 1 A total of 982 observations from sites in the canopy, litter, and soil layers from **a** seven forest cover types

in **b** 10 climate zones were collected from **c** 254 peer-reviewed publications from 1964 to 2018. According to the Köppen–Geiger system, climate zones were classified into tropical (tropical rainforest, tropical monsoon, and tropical savannah), arid, temperate (temperate and dry summer, temperate and dry winter, and temperate and no dry season), cold (cold and dry winter and cold and no dry season), and polar climates.

Results and discussion

Global distributions of forest water retention

Total water storage (TWS) in global forest ecosystems is estimated to be 22,662.47 km^3 (14,984.15–37,411.59 km^3) based on the integrated water-storage capacity method (Fig. 2a; Supplementary Fig. 1). This water accounts for ~10% of all freshwater available to humans and ecosystems (200,000 km^3)[17]. In the longitudinal direction, the distribution of TWS has three peaks corresponding to the Amazon Plain (255.10 km^3 between 52°W and 78°W), Congo Basin (192.70 km^3 between 14°E and 28°E), and Malaysia (175.24 km^3 between 101°E and 114°E). In the latitudinal direction, the distribution has two peaks: one at high latitude (319.63 km^3 between 47°N and 65°N) and one crossing the equator (591.15 km^3 between 9°N and 14°S; Fig. 2a). Water storage in the forest canopy, litter, and soil layers accounts for 57.31% (12,987.15 km^3), 0.79% (178.92 km^3), and 41.90% (9,496.40 km^3) of the TWS, respectively. Among forest types, the highest amount of water storage is found in evergreen broadleaf forests (7,370.00 km^3) followed by woody savannas (5,004.73 km^3) and savannas (4,021.73 km^3); water storage is only 126.29 km^3 in deciduous needleleaf forests.

The global mean value of WRC is 456.71 mm, and WRC reaches more than 1000 mm in the Andes Mountains (0°N–10°N) and the Malay Islands (Fig. 2a). Our results indicate that forest ecosystems had a higher WRC than all terrestrial ecosystems (mean of 179 mm and a maximum of 607 mm in the tropics) from 1961 to 1995[18]. In general, global WRC decreases moving from the equator to the poles, from the coast to inland, and from the mountains to lowlands (Fig. 2a).

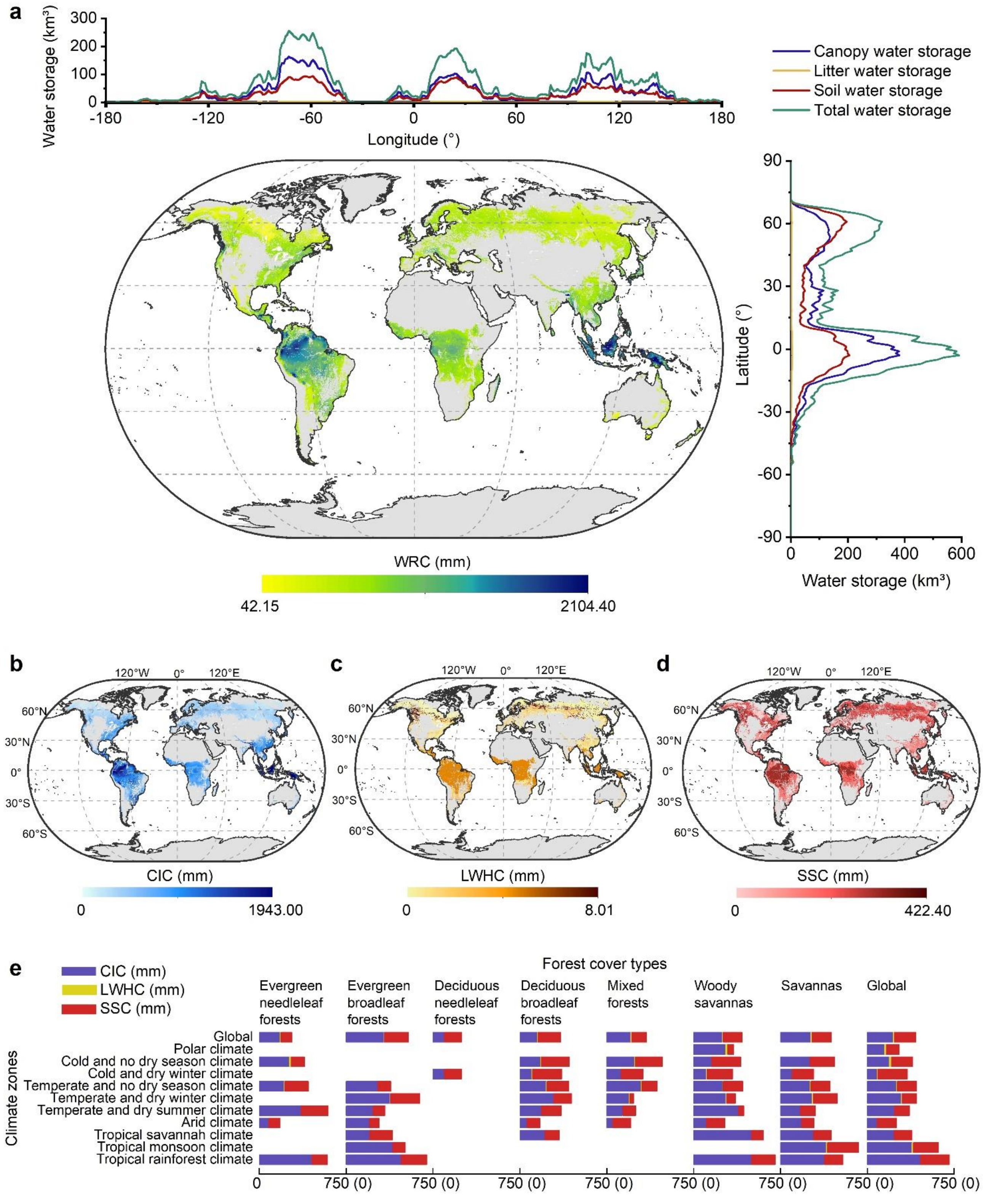

Fig. 2 Global patterns of **a** WRC, **b** CIC, **c** LWHC, and **d** SSC in **e** different forest types and different climate zones. Charts on the top and right of **a** show the longitudinal and latitudinal distributions of TWS, respectively.

At the global scale, large differences in forest WRC are observed among regions in each layer. High values (> 500 mm) of canopy interception capacity (CIC) are found in regions near the equator and mountainous coastal areas at mid-high latitudes, including the coastal mountains in western Canada, Central America, the Amazon, eastern Madagascar, southern Japan, the Arakan Mountains and Malay Islands in Asia, and western New Zealand (Fig. 2b). The mean value of global CIC is 243.57 mm, and CIC reaches 494.77 mm in tropical rainforest climate zones and woody savannas. Litter water-holding capacity (LWHC) only accounts for 0%–4.69% of WRC with an average value of 1.49 mm globally. The range of LWHC (0–7.22 mm) in this study is consistent with that reported by Liu et al. (0–8 mm)[19]. High values of LWHC are distributed in coniferous forests at mid-high latitudes in the Northern Hemisphere, southeast of the Qinghai–Tibet Plateau, and south of 45°S in Chile (Fig. 2c). Although our results suggest that litter contributes little to WRC, litter can store water amounts equal to 200%–225% of the litter dry weight[20, 21] and can regulate the water available for soil infiltration and runoff[2, 22]. Soil water-storage capacity (SSC) reaches 422.40 mm with a mean of 161.53 mm at the global scale (Fig. 2d). SSC is lower than CIC in all regions except those with cold climate zones or deciduous forest types (Fig. 2e). Among forest/climate types, the highest mean WRC (704.32 mm) is found in evergreen broadleaf forests in tropical rainforest climate zones, whereas the lowest mean WRC (171.21 mm) is found in evergreen needleleaf forests in arid climate zones (Fig. 2e).

Single-factor analyses of CIC, LWHC, SSC, and WRC

We further analyzed the relationships between individual factors and CIC, LWHC, SSC, and WRC. The factors analyzed were location (latitude), terrain factors (elevation and slope), climatic factors [mean annual precipitation (MAP), mean annual temperature (MAT), and evapotranspiration], forest structure factors [stand age, stand density, canopy density, tree height, diameter at breast height (DBH), leaf area index (LAI), and interception rate], litter characteristics (litter thickness and litter mass), and soil physical properties (soil depth, bulk density, soil texture, capillary porosity, non-capillary porosity, and total capillary porosity).

Global CIC decreases moving from 0° to 50°N (Supplementary Fig. 2), consistent with the results reported by Wu et al. for CIC in China from 20°N to 50°N[23]. CIC also decreases with increasing elevation (Supplementary Fig. 2), resulting in significant negative correlations between elevation and CIC in different climate zones and forest cover types (Fig. 3; Supplementary Fig. 5). However, in tropical climate zones, some non-significant positive correlations are observed between CIC and elevation; these might be explained by the remarkable ability of tropical high-altitude forests to intercept fog and cloud droplets[24]. MAP shows significant positive correlations with CIC in different regions, and its correlations are stronger than those of other factors (Fig. 3), consistent with previous results[25]. In contrast to MAP, evapotranspiration has a significant negative correlation with global CIC, especially in the temperate and dry winter climate zones (Fig. 3). This may be related to the large contribution of evapotranspiration to the basin water balance in this climate zone, where evapotranspiration may exceed 90% of precipitation[24]. CIC is also positively correlated with tree height, canopy density, and LAI in different regions (Fig. 3). For example, thinning led to a 42%

reduction in canopy interception in a Japanese cedar forest[26, 27]. Recent studies have found interception rates varying from 7% for a LAI of 0.3 to 25% for a LAI of 4.8 in Cordoba, where the local MAP is 606 mm[28, 29]. Wang et al. also reported a significant positive correlation between CIC and LAI in a *Larix principis-rupprechtii* plantation ($R^2 = 0.99$)[30]. Similarly, canopy density is related to LAI and therefore is an essential factor in CIC (Fig. 3 and Supplementary Fig. 2), consistent with the findings of Fleischbein et al[31].

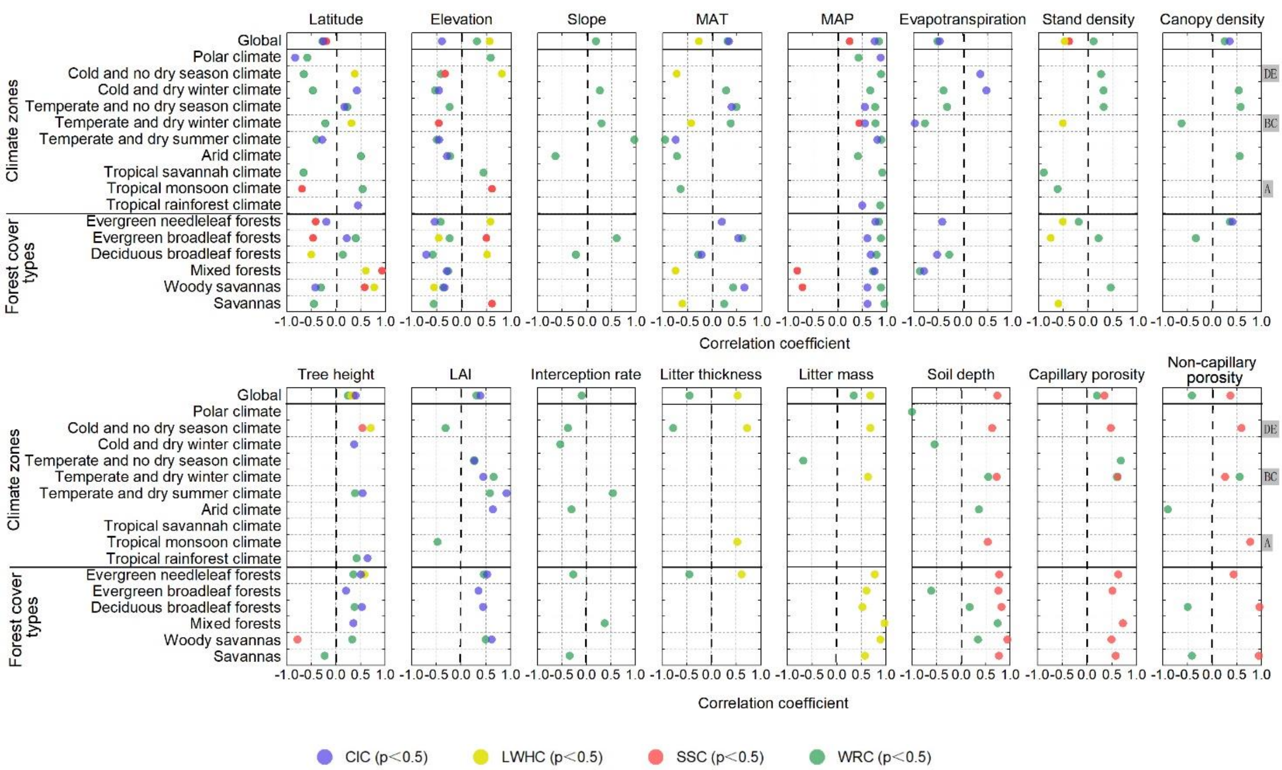

Fig. 3 Spearman correlations between single factors and CIC, LWHC, SSC, and WRC in different climate zones and forest cover types at (significance indicated by $P < 0.05$). Due to the lack of data in the litter and soil layers, climate zones are combined into tropical (A), arid and temperate (BC), and cold and polar (DE) climate zones on the right side.

LWHC increases with increasing latitude (Supplementary Figs. 2 and 3), while the opposite trend is observed for CIC. This phenomenon can be explained by the fact that tropical forests capture more precipitation in lower latitudes, resulting in larger CIC at lower latitudes[19, 32]. However, in the mid-high latitudes, litter mass and litter thickness increase with latitude, and more water is retained because lower temperature leads to lower microbial activity and slower litter decomposition[33]. The results of this study confirm that globally, LWHC is significantly positively correlated with elevation and tree height, while it is significantly negatively correlated with MAT (Fig. 3 and Supplementary Fig. 5). Supplementary Fig. 3 shows that with increasing stand age, LWHC first decreases and then increases. This finding is supported by a comparative analysis indicating LWHC values for young, medium, and mature forests of 8.22, 7.61, and 10.78 mm, respectively[28].

At a global scale, there is a significant negative correlation between SSC and latitude (Fig. 3 and Supplementary Figs. 4 and 5). SSC is positively correlated with elevation in the tropics but negatively correlated with elevation in temperate and cold climate zones, although these correlations are not significant on a global scale (Fig. 3 and Supplementary Fig. 5). SSC is positively correlated with soil depth, non-capillary porosity, and total capillary porosity at both the global and zonal scales (Fig. 3 and Supplementary Fig. 5).

In summary, at a global scale, WRC is significantly positively correlated with elevation, slope, MAT, MAP, tree height, LAI, stand density, canopy density, litter mass, and capillary porosity and negatively correlated with latitude, evapotranspiration, interception rate, litter thickness, and non-capillary porosity (Fig. 3 and Supplementary Fig. 6). Among the analyzed factors, the strongest correlations with WRC are observed for evapotranspiration, canopy density, tree height, LAI, interception rate, litter thickness, and non-capillary porosity ($R^2 \geq 0.80$, $P < 0.01$; Fig. 4).

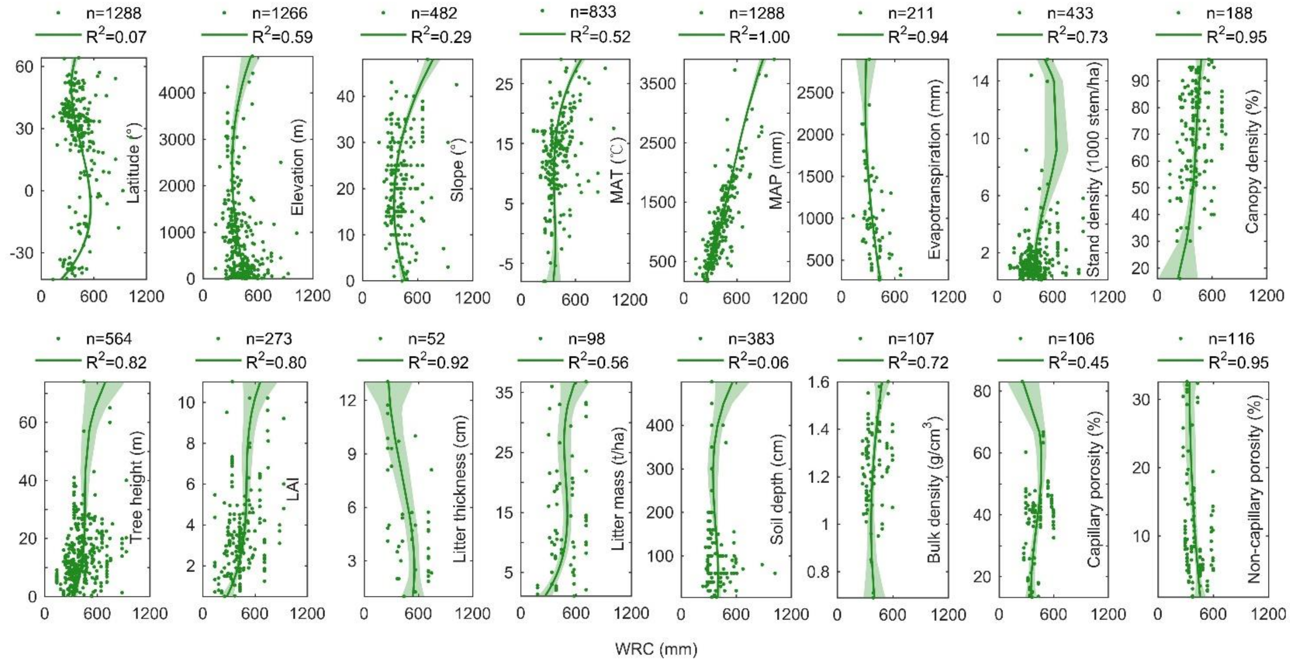

Fig. 4 Fitting curves between WRC and individual factors (P < 0.01). The shaded bands show the 95% confidence intervals.

Multifactor analyses of CIC, LWHC, SSC, and WRC

Forest structure factors including vegetation cover, LAI, and interception rate explain most of the observed variation in CIC (Fig. 5a and Supplementary Fig. 7). Vegetation cover has a significant positive effect (total coefficient = 0.69) on CIC (Supplementary Fig. 7), in agreement with Wei et al., who reported that vegetation cover is a dominant factor affecting global water resources in forested regions[4]. LAI also has a positive effect (total coefficient = 0.39) on CIC, while elevation has a negative effect (total coefficient = –0.25). Our results indicate that MAP has a small, indirect negative effect (standardized coefficient = –0.11) on CIC through interception rate. That is, the interception rate is lower near the equator, which may be because it does not continue to increase with additional precipitation after interception has become saturated[34].

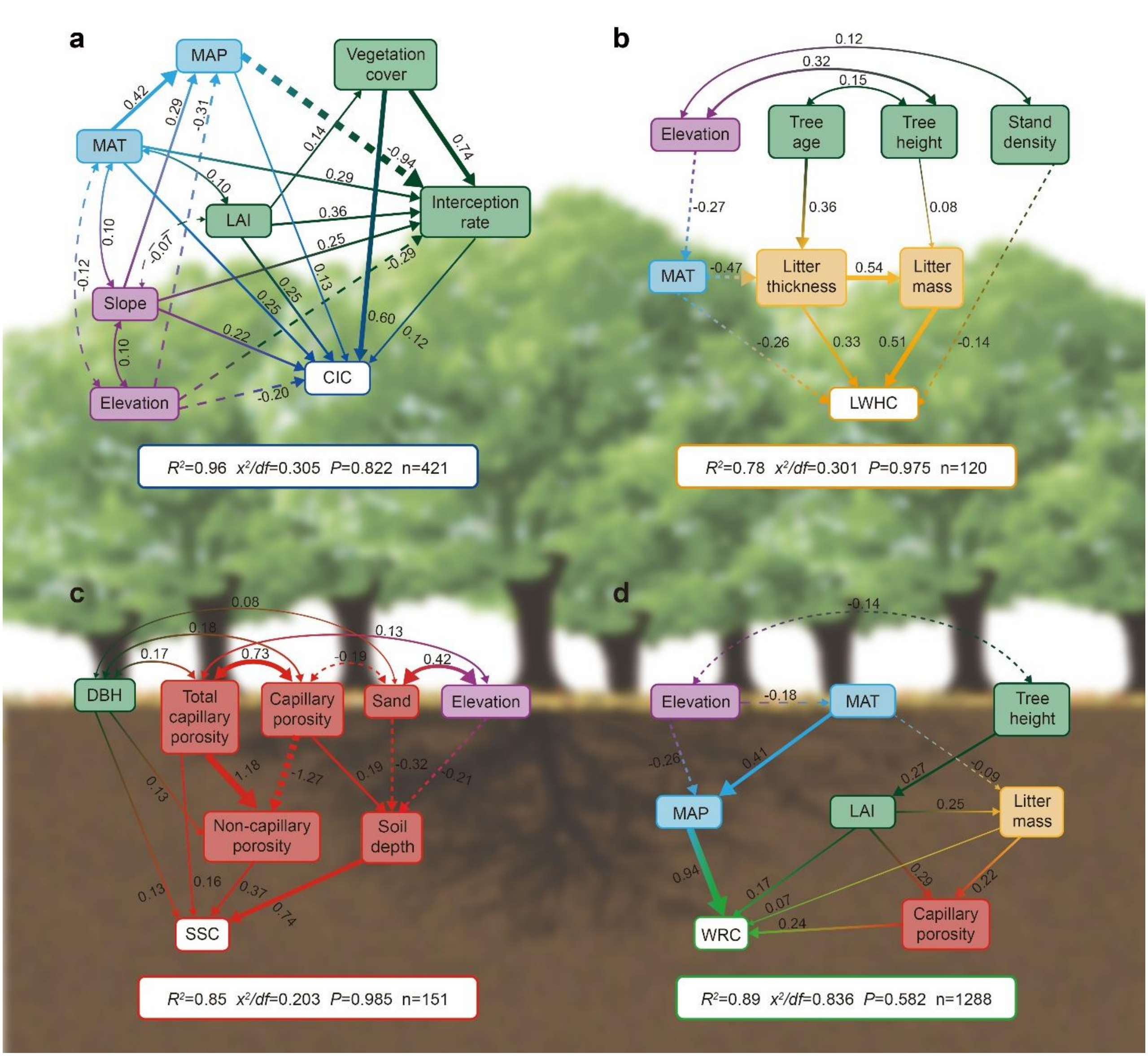

Fig. 5 Effects of multiple factors on **a** CIC, **b** LWHC, **c** SSC, and **d** WRC based on SEM. Purple boxes represent terrain factors, blue boxes represent climatic factors, green boxes represent forest structure factors, yellow boxes represent litter characteristics, and red boxes represent soil physical properties. Lines represent causation if straight or correlation if cambered; solid and dashed lines indicate positive and negative correlations, respectively.

Litter characteristics can explain 78% of the variation in LWHC (Fig. 5b and Supplementary Fig. 7). Litter thickness (total coefficient = 0.61) and litter mass (total coefficient = 0.51) have positive effects on LWHC. High LWHC values are concentrated in high-latitude and high-altitude areas, indicating again that MAT has a negative effect (total coefficient = –0.55) on LWHC, while elevation has a positive effect (total coefficient = 0.15) on LWHC.

Soil physical properties, DBH, and elevation explain 85% of the variation in SSC (Fig. 5c and Supplementary Fig. 7). Among the factors, soil depth has the greatest positive effect (total coefficient = 0.74) on SSC. Non-capillary porosity provides infiltration channels for saturated soil water, and its effect on SSC (total coefficient = 0.37) is opposite that of capillary porosity (total coefficient = –0.32), which contributes to the storage of water for root resorption and soil evaporation. Total capillary porosity has a positive effect (total coefficient = 0.59) on SSC. Consistent with the canopy layer, elevation has a weak negative effect (total coefficient = –0.16) on SSC.

Overall, the five factor types (terrain factors, climatic factors, forest structure factors, litter characteristics, and soil physical properties) explain 89% of the variance in WRC (Fig. 5d and Supplementary Fig. 7). Among factors, elevation exerts an indirect negative effect (total coefficient = –0.31) on WRC through its effects on MAT (standardized coefficient = –0.18) and MAP (standardized coefficient = –0.26). MAP has the strongest positive effect (total coefficient = 0.94) on WRC. MAT has a small indirect effect on WRC through its negative effect on litter mass (standardized coefficient = –0.09); however, this small effect is offset by the strong indirect positive effect of MAT on WRC through its influence on MAP. LAI and capillary porosity also have positive effects on WRC (total coefficient = 0.28 and 0.24, respectively), consistent with the findings of a global analysis of dynamic water balance[35]. In conclusion, among the factor types, climate factors have the strongest positive effects on WRC followed by forest structure factors, soil physical properties, and litter characteristics. Meanwhile, elevation has a negative effect on WRC. Most past studies have considered only the effects of single climatic factors such as precipitation, evapotranspiration, and runoff. In contrast, the SEM approach applied in this study shows that terrain factors, forest structure factors, litter characteristics, and soil physical properties all have essential effects on WRC. Therefore, multiple factors should be included in existing ecohydrological models, and interactions between factors should also be considered.

Implications

Our results based on site observations from the literature present a clear global pattern of water retention in the forest canopy, litter, and soil layers. CIC is mainly dominated by MAP and vegetation cover, and CIC generally decreases moving from tropical to cold climate zones. High values of LWHC are distributed in high-latitude and high-altitude regions due to the negative affect of MAT on LWHC. High SSC values are dispersed in tropical, temperate, and cold climate zones, and SSC is mainly determined by soil properties. The results not only provide a reference for assessing forest management and ecosystem services; they also serve as a benchmark to improve evaluation models for ecosystem services related to water retention. Extending regional models to the global scale results in large errors, making it necessary to use site observation data to benchmark the models in the future[36]. In other words, the canopy, litter, and soil data for a large number of observation sites can be simulated on a global scale based on machine learning to generate global products for model correction[36]. Comparisons of the model results with site observation data can be used to reduce the uncertainty of the model[37]. Therefore, environmental variables and forest ecosystem characteristics should be incorporated into models to improve simulation accuracy; some of these factors are currently ignored, particularly in large-scale evaluation models.

In this study, the effects of various factors were explicitly examined through a global synthesis of multiple factors affecting water retention in the forest canopy, litter, and soil layers, thereby extending the results from small-scale observational studies to a global scale. Our findings suggest that both nature (e.g., terrain, forest structure, litter characteristics, and soil properties) and nature drivers (e.g., climate change and land use change) have substantial effects on water retention in forest ecosystems. Globally, four dominant factors (MAP, tree height, litter thickness, and soil porosity) show synergic relationships with WRC, while evapotranspiration has an inhibitory effect on WRC. It should be noted that the spatial and temporal distributions of data from the canopy, litter, and soil layers used in this study are uneven among different climate zones and forest cover types (Fig. 1). Nevertheless, the collected observational data cover 99.15% of forest types and 92.79% of climate zones. Although the observational data span a large range of years, nearly two decades of observations account for over three-quarters of all the data. Thus, improving the accuracy of global observational data[10] is critical to refine and differentiate the different factors affecting water retention over time. For example, unmanned aerial vehicle remote sensing can be used to control the relative errors in measurements of forest structure factors (e.g., tree height, crown width, and DBH) [38], improve the efficiency of these measurements, and provide digitized data resources for forestry research.

With the worsening of global ecological issues, the human dimension of the forest–water nexus has become more evident in recent years[39]. As the terrestrial human footprint continues to expand, the amount of native forest free from severe damage from human activities is in precipitous decline[40]. Of the remaining forests, 82% are directly degraded by human actions such as industrial logging, urbanization, agriculture, and infrastructure development[41, 42]. Issues such as land degradation and increasing population affect the ability of forests to provide water-related ecosystem services, resulting in water insecurity[43]. Almost two-thirds of biological habitats and 80% of the world's population are located in areas facing water insecurity[44]. To lessen the freshwater shortage caused by population growth, thinning and burning are often conducted to increase runoff in forest basins[8, 45]. These unsustainable behaviors contribute to ecosystem destruction and freshwater depletion. In addition, changes in precipitation along with the melting of snow and ice have affected forest hydrological systems in many regions, resulting in decreased river flow, decreased stand density, and increased drought[46]. Our results show that intact forests[47, 48] in Malaysia, the Amazon Basin, and the Zaire Basin have a mean WRC value of 670.24 mm, 200 mm higher than the global average (Fig. 2a; Supplementary Table 1). Therefore, virgin tropical forests with high WRC values should be protected and monitored. Given the broad distributions of savannas and woody savannas (Fig. 1a), these forest types should also be valued for their WRC, and management policies should be formulated accordingly. Furthermore, in these critical ecological regions for water retention, the main controlling factors should be divided by climate zone and forest type.

With the implementation of sustainable development, new driving forces and interactions with forest ecohydrology will constantly emerge[49]. In the face of population growth, deforestation, and the disappearance of water sources, many ecological restoration projects have been successful in curbing land degradation and improving ecosystem services, including green dam construction in five North African countries since 1970, the Three-North Shelter Forest Program, the Grain for Green Program, and the Natural Forest Protection Project in China over the past 50 years[50, 51]. These projects have transformed wasteland and farmland into grassland and woodland in ecologically fragile regions, thereby preventing desert expansion and promoting soil and water retention. Conversely, another view holds that some regions should not restore ecosystems by afforestation because regions with MAP values lower than 400 mm do not retain sufficient water to support trees[52, 53, 54]. In the future, the effects of human activities on forest ecology and hydrology may be two sided, making the attribution of forest water retention more complicated. However, forest-driven water cycles are poorly integrated into global decision-making regarding land use and water management[24]. The next step is to establish science–policy–practice scenarios to guide the management of global forest–water resources and their related ecosystem services.

Methods

Literature data screening and extraction

We collected peer-reviewed literature for assessing water retention in forest ecosystems (Supplementary Fig. 9). First, we searched the Web of Science database using the following keywords: (1) 'forest' AND ('canopy' OR 'interception*') AND ('rainfall*' OR 'precipitation*'); (2) 'forest' AND (('litter' AND 'maximum* water holding*') OR ('litter mass' OR 'litter storage')); (3) 'soil' AND 'forest' AND ('depth*' OR 'thickness*' OR 'porosity' OR 'water storage' OR 'effective storage capacity' OR 'available water holding capacity'); (4) ('forest' OR 'ecosystem' OR 'water retention') OR ('canopy' OR 'interception') OR ('litter' AND 'water holding') OR ('soil water storage' OR 'porosity'). Out of the resulting articles, we included those published in English journals that were based on field observation data; articles with remote sensing data, digital mapping data, or model-based simulation data were excluded. The literature was then classified by vertical forest layer, and the data were compiled to establish the water retention database.

Overall, the search resulted in the inclusion of 254 articles published from 1967 to 2019 containing data measured from 1964 to 2018 (Fig. 1c). The data corresponded to 982 data sites, with 744 sites in the forest canopy layer, 120 in the litter layer, and 151 in the soil layer (Fig. 1a). The extracted metadata mainly included the following: background information (author, title, publication time, and observation period); stand conditions (coordinates, elevation, climate zones, forest cover types, MAT, MAP, and evapotranspiration); canopy parameters (stand age, stand density, vegetation cover, canopy density, LAI, tree height, DBH, rainfall duration, and interception rate); litter parameters (litter thickness, litter mass, and maximum water-holding rate); and soil parameters (soil depth, bulk density, sand content, clay content, silt content, capillary porosity, and non-capillary porosity).

Spatial data sources and processing

Spatial raster data included DEM, MAP, land cover, soil physical properties, climate classification, and intact forest areas, and all resolutions were converted to 0.083°. DEM data were obtained from ASTER GDEM v3 (http://www.gdem.aster.ersdac.or.jp). The MAP data were based on the monthly precipitation dataset from the Climatic Research Unit (https://crudata.uea.ac.uk/cru/data/hrg/) corresponding to 1990–2018. Among the data collected from the literature, 90.94% corresponded to 1990–2018 (Fig. 1c). MODIS land cover data (MCD12Q1) for seven forest cover types were used in this study (Figs. 1a and 1b). Soil data were from the soil profile database of the World Soil Information Service. The Köppen–Geiger climate classification map was obtained from www.gloh2o.org/koppen (Fig. 1b). The intact-forest-cover data are available at http://www.intactforests.org[48].

Integrated water storage capacity method

The integrated water storage capacity method was used to estimate WRC and TWS using equations (1) and (2):

$$\mathrm{WRC} = \mathrm{CIC} + \mathrm{LWHC} + \mathrm{SSC}, \tag{1}$$

and

$$\mathrm{TWS} = \sum_{i=1}^{n} (\mathrm{CIC}_i + \mathrm{LWHC}_i + \mathrm{SSC}_i) \times A_i \times 10^{-6}, \tag{2}$$

where A represents the patch area (km^2), and i represents a specific patch. CIC, LWHC, and SSC were respectively calculated using equations (3)–(5):

$$\mathrm{CIC} = \mathrm{MAP} \times \mathrm{IR}, \tag{3}$$

$$\mathrm{LWHC} = \mathrm{LM} \times \mathrm{WHR} \,/\, 10, \tag{4}$$

and

$$\mathrm{SSC} = \mathrm{SD} \times \mathrm{NCP}, \tag{5}$$

where IR is the interception rate (%), LM is the litter mass (t/ha), WHR is the litter water-holding rate (%), SD is the soil depth (mm), and NCP is the non-capillary porosity (%).

Seventy regions were identified according to the seven forest cover types and 10 climate zones, and each region was ensured to have similar climatic and vegetation conditions (Supplementary Fig. 8). For regions with no observable data, data from adjacent regions were used. We then calculated the mean values and standard deviations (σ) of IR, LM, WHR, and NCP for each region. The mean values were used to calculate WRC (Fig. 2), and the mean values ± σ were used to test the dispersion of WRC (Supplementary Fig. 1).

Polynomial curve fitting

Based on the least-squares method, we fitted the optimal curve of water retention capacity for a potential controlling factor using functions (6) and (7):

$$p = \text{polyfit}\ (x, y, n), \tag{6}$$

and

$$y1 = \text{polyval}\ (p, x), \tag{7}$$

where x, y represents the coordinates of scatter points to be fitted, n represents the power of polynomial fitting, p represents the coefficient of polynomial fitting, and $y1$ represents the fitting result using the p coefficient.

Statistical analysis

Due to the non-linear and non-continuous distributions of scatter points, spearman correlation analysis was selected for further univariate analysis. The correlations were also evaluated for the seven forest cover types and 10 climate zones.

Finally, the relationship between multiple factors and water retention capacity was tested by SEM. SEM is based on a complicated regression relationship composed of multiple factors allowing the effects of single factors on the population to be analyzed along with the mutual relationships between single factors simultaneously. Factors can be divided into direct driving forces and indirect driving forces that produce either positive or negative effects[49]. The total effect of a certain driving force on the ecosystem is the sum of the direct and indirect effects. SEM has a variety of evaluation indexes: a R^2 value close to 1 indicates that the observed variance in the model is well explained by the considered controlling factor(s); a probability value (P) close to 1 indicates an excellent matching effect between the model and the result; a ratio of chi-squared to freedom (x^2/df) less than 3 and a root-mean-square error of approximation less than 0.05 indicate that the model fits well. Using 982 observed data, we applied SEM to global forest regions and specified the factors controlling each forest ecohydrological process.

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Figures

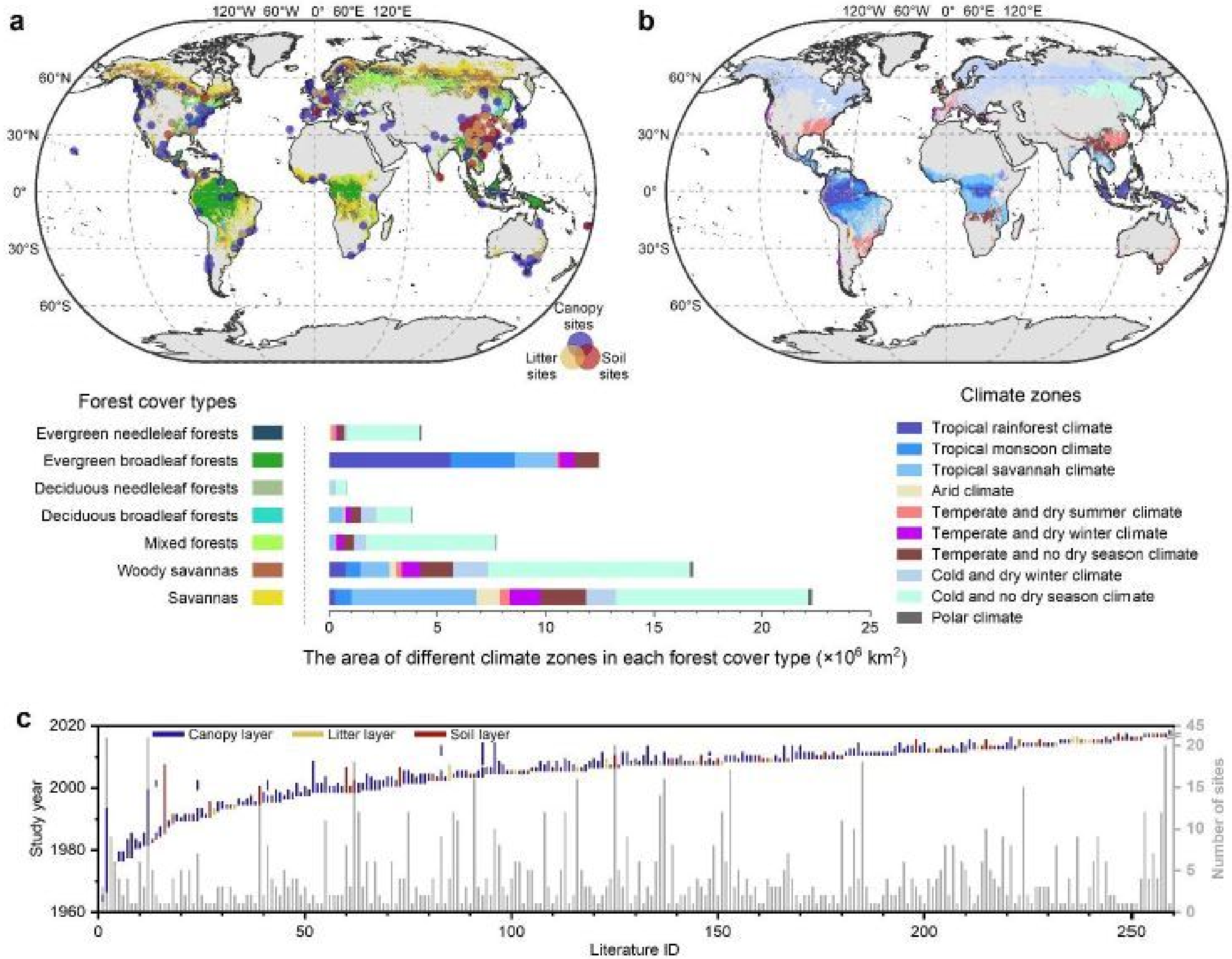

Figure 1

A total of 982 observations from sites in the canopy, litter, and soil layers from a seven forest cover types 4 in b 10 climate zones were collected from c 254 peer-reviewed publications from 1964 to 2018. According to the Köppen–Geiger system, climate zones were classified into tropical (tropical rainforest, tropical monsoon, and tropical savannah), arid, temperate (temperate and dry summer, temperate and dry winter, and temperate and no dry season), cold (cold and dry winter and cold and no dry season), and polar climates. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

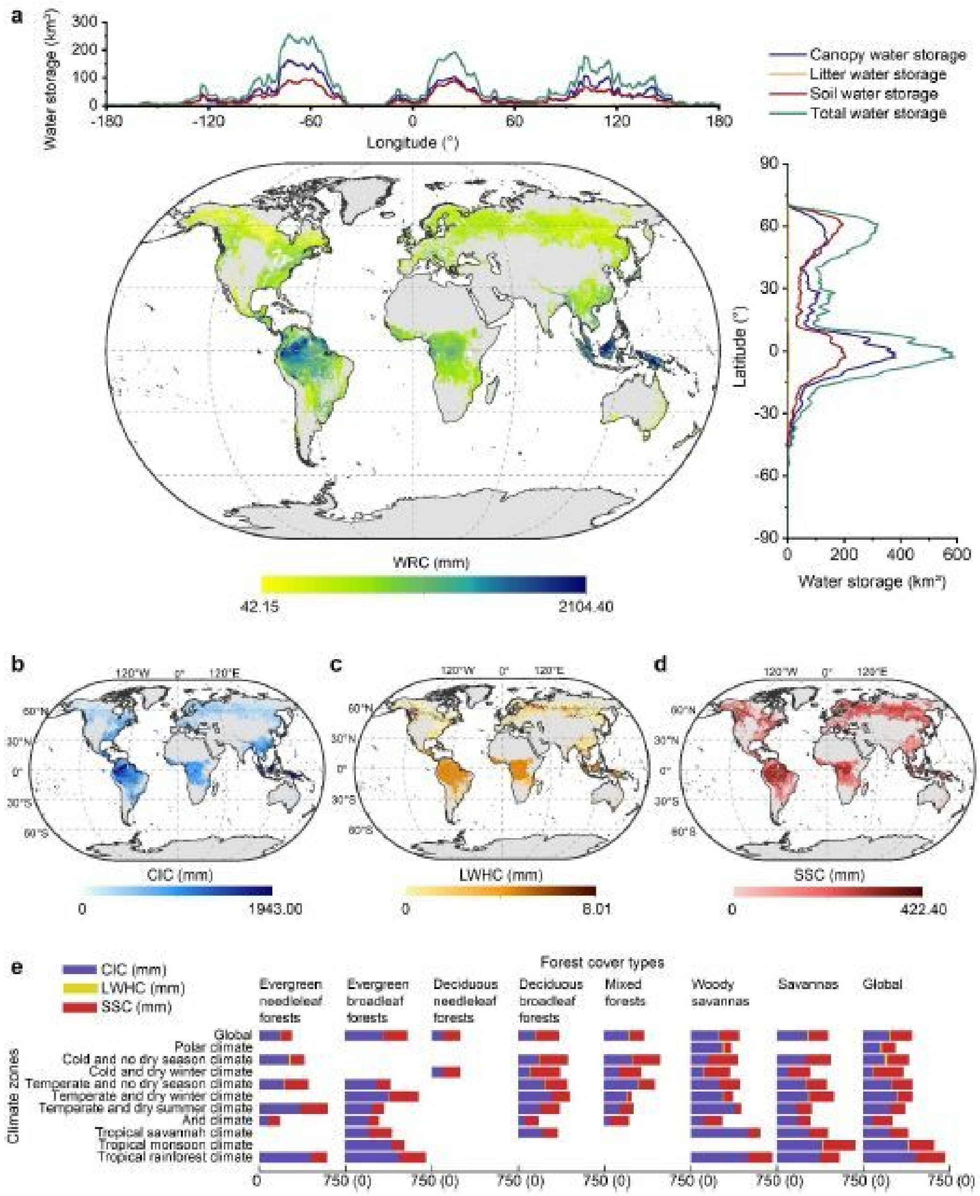

Figure 2

Global patterns of a WRC, b CIC, c LWHC, and d SSC in e different forest types and different climate zones. Charts on the top and right of a show the longitudinal and latitudinal distributions of TWS, respectively. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

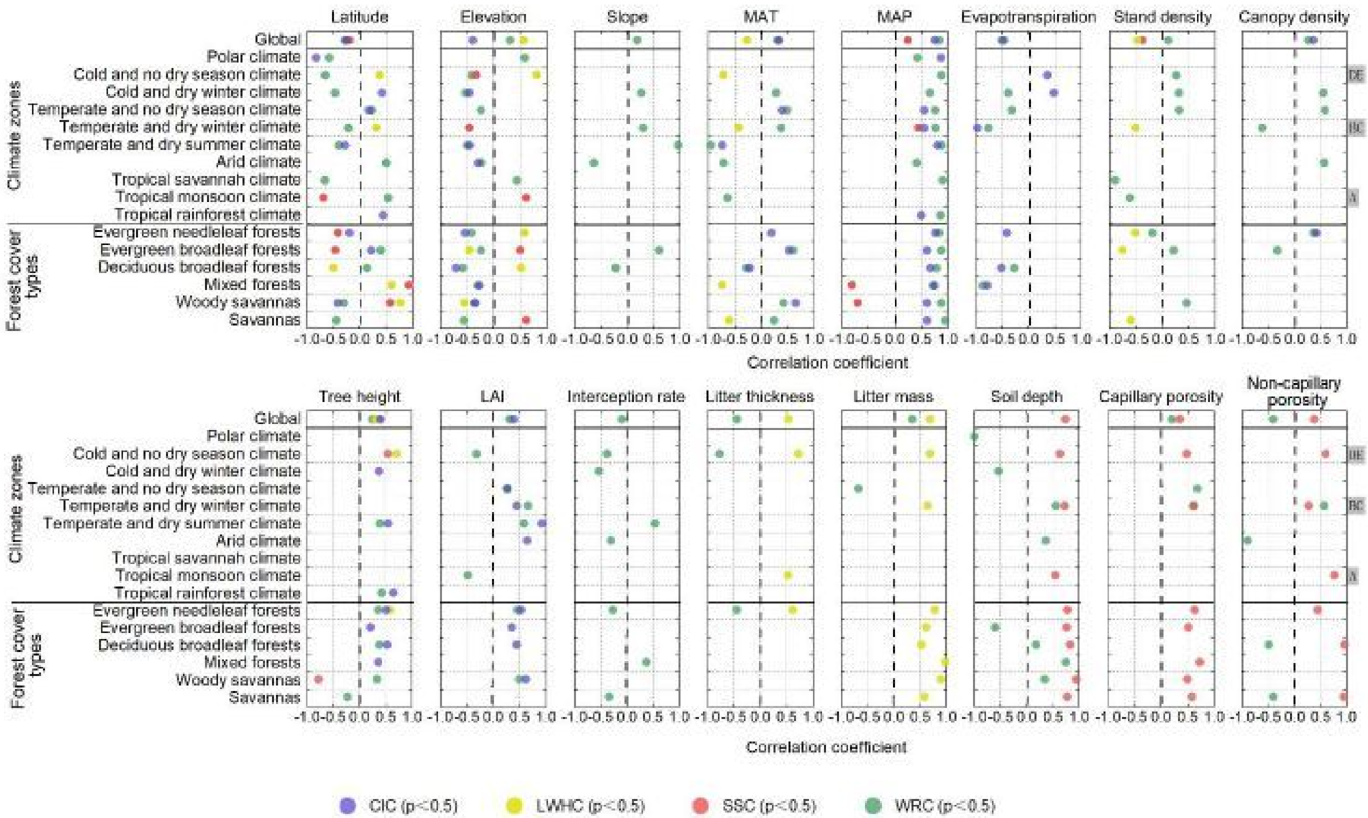

Figure 3

Spearman correlations between single factors and CIC, LWHC, SSC, and WRC in different climate zones and forest cover types at (significance indicated by P 0.05). Due to the lack of data in the litter and soil layers, climate zones are combined into tropical (A), arid and temperate (BC), and cold and polar (DE) climate zones on the right side.

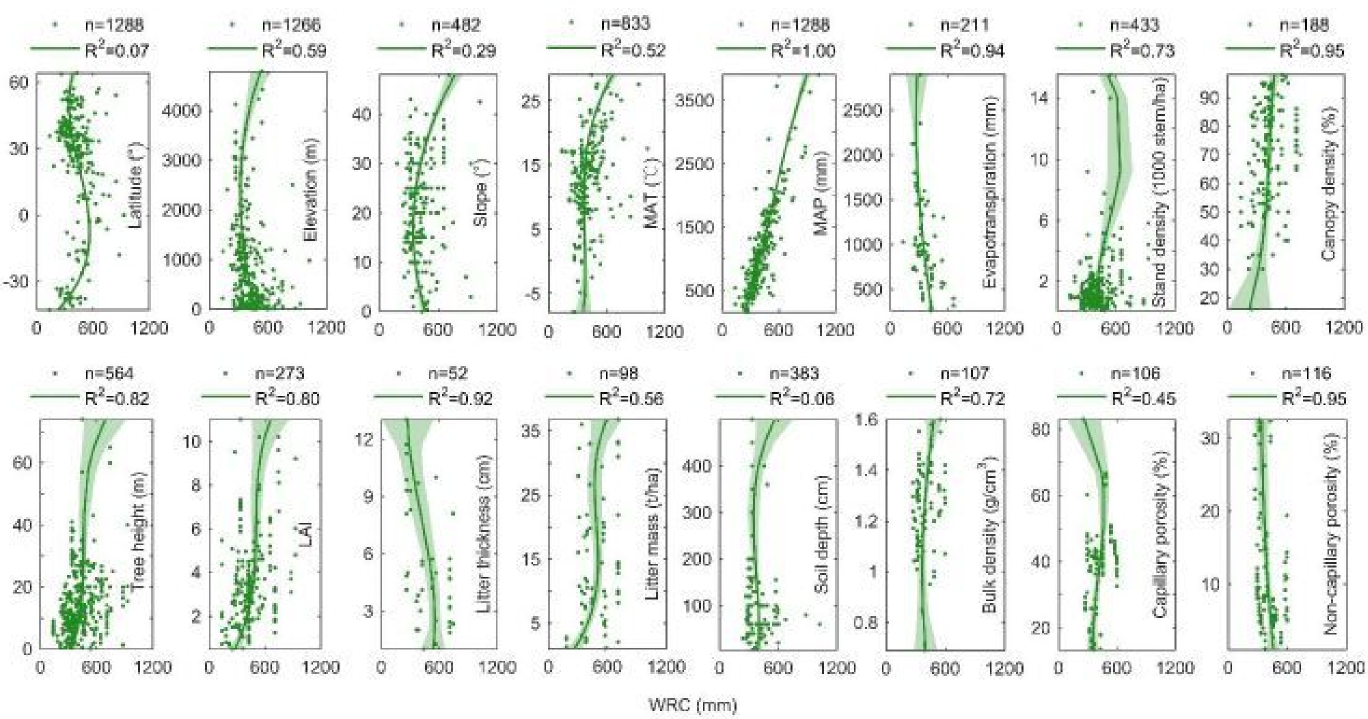

Figure 4

Fitting curves between WRC and individual factors (P < 0.01). The shaded bands show the 95% confidence intervals.

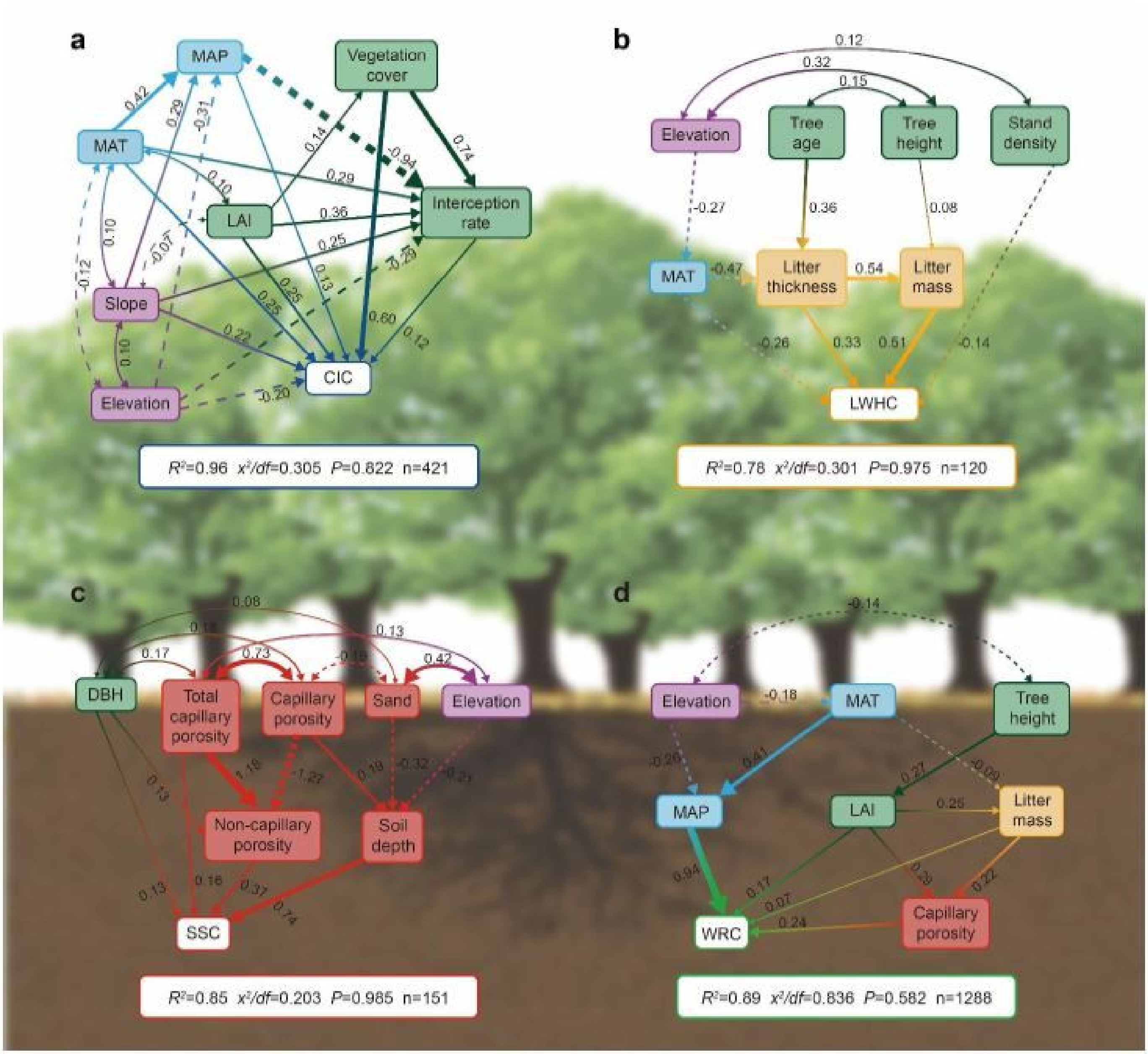

Figure 5

Effects of multiple factors on a CIC, b LWHC, c SSC, and d WRC based on SEM. Purple boxes represent terrain factors, blue boxes represent climatic factors, green boxes represent forest structure factors, yellow boxes represent litter characteristics, and red boxes represent soil physical properties. Lines represent causation if straight or correlation if cambered; solid and dashed lines indicate positive and negative correlations, respectively.

Supplementary Files

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- SupplementaryinformationGlobalwaterretentioninforestcanopylitterandsoillayersanditscontrollingfactors.pdf
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